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High granularity tracker based on a Triple-GEM optically read by a CMOS-based camera

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ABSTRACT: The detection of photons produced during the avalanche development in gas chambers has been the subject of detailed studies in the past. The great progresses achieved in last years in the performance of micro-pattern gas detectors on one side and of photo-sensors on the other provide the possibility of making high granularity and very sensitive particle trackers.
In this paper, the results obtained with a triple-GEM structure read-out by a CMOS based sensor are described. The use of an He/CF_4 (60/40) gas mixture and a detailed optimization of the electric fields made possible to obtain a very high GEM light yield. About 80 photons per primary electron were detected by the sensor resulting in a very good capability of tracking both muons from cosmic rays and electrons from natural radioactivity.

KEYWORDS: Micro-pattern Gas Detectors; GEM; CMOS; Particle Tracking.

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Contents

Introduction

Micro-pattern gas detectors have proven to be versatile devices for high resolution particle tracking. One of the most successful micro-pattern technologies developed so far is the Gas Electron Multiplier (GEM), introduced in 1996 at CERN [1]. Electrons produced in a gas mixture by ionizing particles are multiplied within the GEM foil channels where a high electric field is present. During the multiplication process, photons are produced along with electrons by the gas through atomic and molecular de-exitation.

CMOS based photo-sensors can be exploited to read-out this light. Given their impressive development in last years, commercial CMOS detectors offer a very high granularity together with a very low noise level. Primary electrons, produced by ionizing particles, are multiplied in a GEM based structure and the image of the holes where the avalanches happen can be acquired. In this way, not only the total amount of light (proportional to the energy realeased in gas), but also the position of the avalanches can be recorded. The projection of the track on the GEM plane can be acquired and used to reconstruct the particle path inside the detector.

1. Experimental set-up

1.1 The triple-GEM structure

The electron multiplication structure was obtained by stacking three 10×10 cm^2 standard GEM foils (70 μm diameter holes with 140 μm pitch) one above the other as shown in Fig. 1.

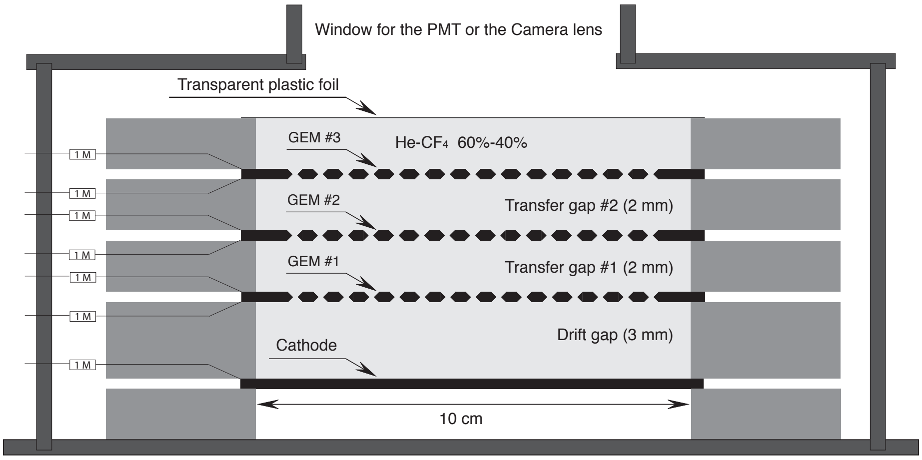

Figure 1. Drawing (not to scale) of the triple-GEM stack. The drift and transfer gaps are shown.

A planar cathode was placed in front of the first GEM to create a 3 mm wide drift gap that represents the main sensitive volume of the system. Two 2 mm wide transfer gaps were left between the three GEM foils. The readout plane was replaced by a transparent plastic foil in order to allow a photo-detection from outside. No electric field was foreseen between the last GEM and the plastic foil. The electrons created in the multiplication were collected on the electrodes of the third GEM. Seven different high voltage channels were used to supply the detector through 1 MΩ protection resistors. The GEM structure was contained in a black box equipped with an upper window used for the image acquisition.

1.2 The gas mixture

All measurements presented in this paper were performed by using a binary gas mixture He/CF_4 (60/40). This mixture is expected to have an emission spectrum with a main contribution around 600 nm characteristic of the CF_4 [2]. In order to evaluate the properties of the gas mixture, a Garfield simulation [4] was performed. The ionization processe due to the crossing of 2 GeV muons in the 3 mm drift gap was studied. As shown in Fig. 2 (left) these muons produce about 10 clusters in average in the 3 mm drift gap. Therefore, the mean distance between two ionization points is about 300 μm.

The distribution of the number of electrons per cluster (Fig. 2, right) has a mean value of 2.3. The total number of primary electrons due to a minimum ionizing muon crossing the drift gap perpendicularly to the GEM plane is thus expected to be around 20.

2. Light yield optimization and measurements

2.1 Signal acquisition and analysis

In order to evaluate the amount of light produced by the GEM stack, a first set of measurements was performed by acquiring the light with an R9800 photo-multiplier[1] with a 25 mm window (GEM-

[1] www.hamamatsu.com/us/en/R9800.html

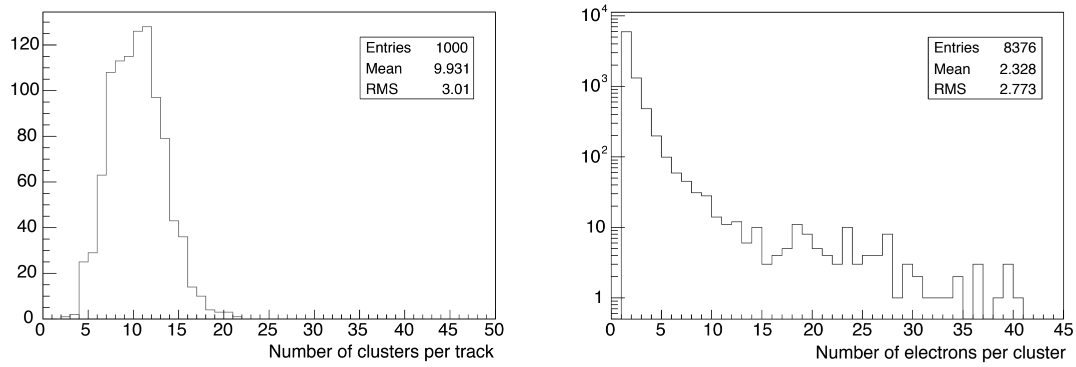

Figure 2. Results of the Garfield simulation: distribution of number of ionization clusters created by 2 GeV muons in the 3 mm wide drift gap (left) and distribution of the number of electrons per cluster (right).

PMT in the following). The detector was placed with the GEM foils in horizontal position (as shown in Fig. 1) so that vertical muons travel about 3 mm in the drift gap. The system was tested by using cosmic rays externally triggered by two NaI scintillators, placed one above and one below the GEM structure. The scintillators have a squared shape with a 10 cm side.

The waveforms of the signals provided by the two PMT reading the NaI and the GEM-PMT were acquired by a Lecroy WavePro 7300 10 GS/s oscilloscope[2]. Figure 3 shows several waveforms of signals produced by the GEM-PMT.

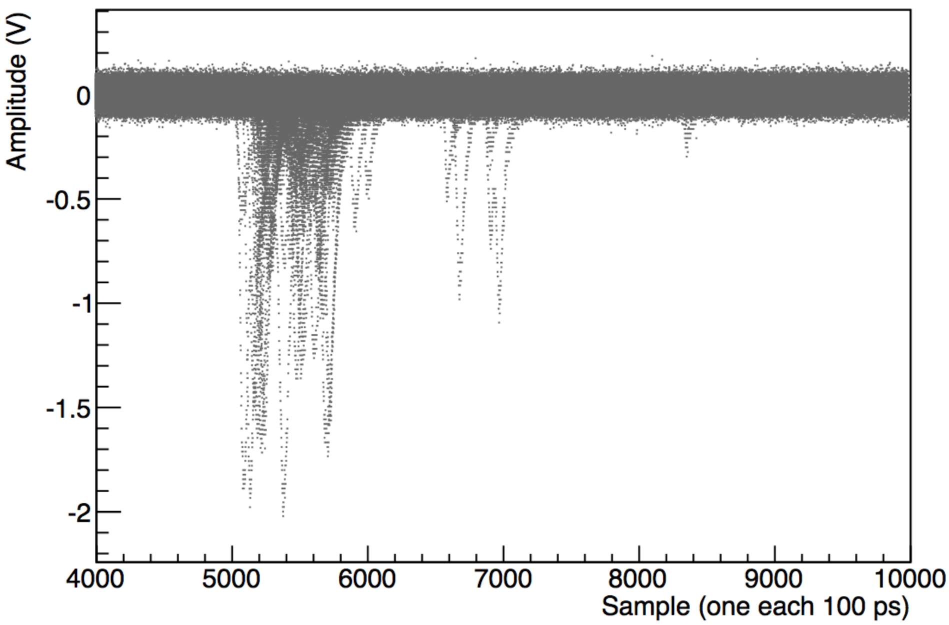

Figure 3. Example of several superimposed waveforms acquired from the GEM-PMT.

[2]teledynlecroy.com/search/default.aspx?q=7300

Each trigger, a 1 μs wide time window (i.e. 10,000 samples) was acquired. Trigger signal is synchronized with the center of the time window. The first half of the window (5,000 samples) was used to evaluate the noise behavior while signals due to crossing muons arrive in the second half of the window. Signals between sample 5,000 and 6,000 are due to light produced by the GEM stack. Few late signals, due to secondary ionization within the detector are also visible. The acquired waveforms have been analysed to evaluate the total charge provided by the GEM-PMT. Since the area of the trigger scintillators is larger than the GEM-PMT window in the main part of triggered events light is produced far away from the GEM-PMT. In Fig. 4 an example of a charge spectrum of the GEM-PMT is shown, with a superimposed "Gauss+Landau" fit. The mean value

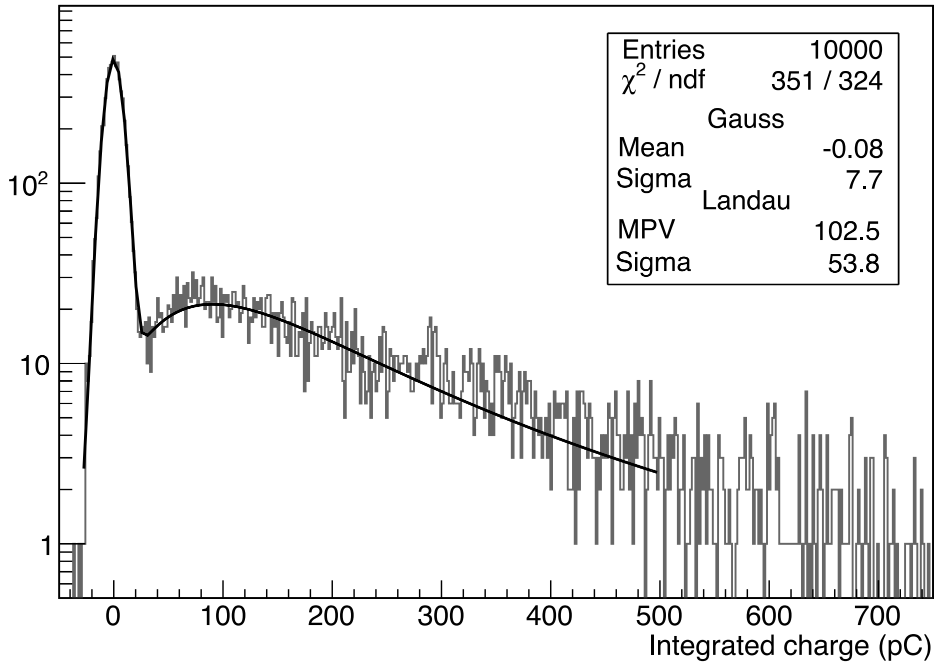

Figure 4. Example of a charge spectrum obtained by integrating the PMT waveforms with a superimposed "Gauss+Landau" fit.

of the Gauss curve gives the pedestal level while the most probable value (MPV) of the Landau curve is used to evaluate the charge (i.e. the light) collected in each configuration.

2.2 Optimization of electric fields

The study of the behavior of the total charge integrated in the PMT signals, made it possible to optimize the electric fields between the GEM in order to maximise the light yield. The voltages across the three GEM foils were kept at 480 V in all measurements.

In a first set of measurements, the amount of collected light was recorded by varying the drift field while keeping the two transfer fields at a value of 1.5 kV/cm. The result, on the left in Fig. 5, shows a maximum for drift field values between 1.5 kV/cm and 2.0 kV/cm. For higher values the light yield decreases because a strong drift field reduces the capability of the GEM in collecting electrons within the multiplication holes (defocusing effect [3]).

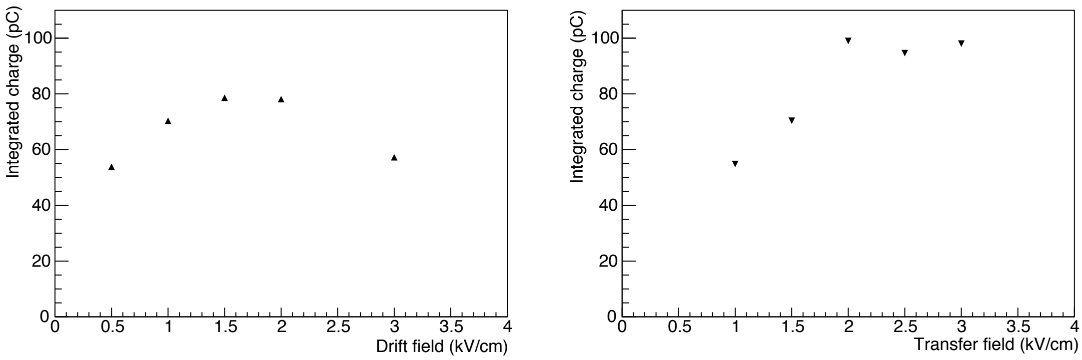

Figure 5. Light yield as a function of the drift field (left) and of transfer fields (right). Data uncertainties are smaller than the markers.

The light yield dependence on the transfer fields was then studied while keeping the drift field at 1.0 kV/cm and by varying both the transfer fields. As shown on the right of Fig. 5, the light yield increases very rapidly while increasing the transfer fields and it is almost stable for values in the range $2.0 \div 3.0$ kV/cm. The charge spectrum in Fig. 4 was obtained in the optimized conditions: drift field at 1.5 kV/cm and transfer fields at 2.0 kV/cm. The PMT response to a single photo-electron was measured by using a calibrated light source and was found to be 0.04 ± 0.01 pC. Therefore it was calculated that in the optimised field configuration, as shown in Fig. 4, about 2500 p.e. were collected in average per cosmic ray crossing.

3. Measurements with a CMOS-based camera

After the light yield was optimised, the acquisition of images by means of a Hamamatsu CMOS-based camera[3] was performed. This camera provides several qualities that make it an optimal choice for this kind of applications:

- *low noise*: nominal level lesser than 2 photons per pixel;
- *high sensitivity*: a quantum efficiency higher than 70% in the CF_4 emission spectral range;
- *high granularity*: 2048 $\times$ 2048 pixels with an area of 6.5 μm $\times$ 6.5μm for a total sensitive surface of 13.3 mm $\times$ 13.3 mm.

3.1 Sensor performance studies

The performance of the CMOS sensor have been investigated by means of a calibrated light source. A 1 mm diameter calibrated light spot was sent to the sensor and the behavior of its response (i.e. the total integrated charge of the sensor, pedestal subtracted) was studied as a function of the light intensity.

Figure 6 shows on the left the results of this study, with a superimposed linear fit. The camera behaviour is well linear in the whole studied range with a response of 0.91 ± 0.01 counts per photon.

[3]Orca flash 4.0. For more details visit www.hamamatsu.com

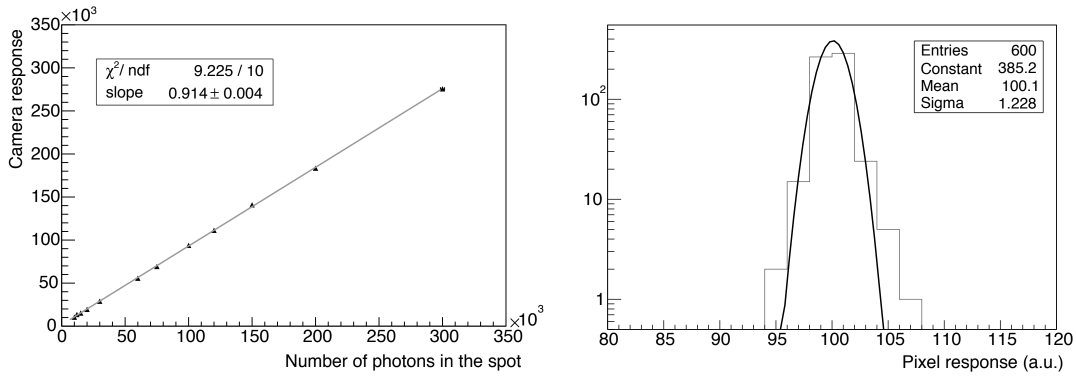

Figure 6. Left: behavior of the response of the camera as a function of the number of photons in the spot. Right: distribution of the response of a not illuminated pixel.

In order to evaluate the noise level, the response of a single pixel was acquired several times while the camera was kept in the dark. The distribution of the values obtained is shown on the right of Fig. 6 with a superimposed gaussian fit. Fluctuations of the pedestal are lower than 2 counts, i.e. lower than two photons per pixel in good agreement with the expectations.

3.2 Cosmic ray measurements

The camera was equipped with lens[4] providing an aperture of f/0.95 excellent for working in low light conditions. It was possible to acquire focused images of the whole GEM area at a distance of 18 cm. Each pixel looked at a surface of about 50μm $\times$ 50μm.

The experimental setup (Fig. 1) was rotated. The GEM and the gaps are put in vertical position. The aim is catching long tracks of muons crossing the drift gap almost parallel to the GEM plane. Thanks to the optical system it was possible to acquire images of cosmic muons crossing the chamber and ionizing the gas mixture within the drift gap.

Twenty tracks were collected in a five minute run. Two examples of recorded images are displayed in Fig. 7. The pictures were taken with an exposure of 100 ms. They show two tracks due to particles crossing the detector. The one on the left is about 29 mm long while the one on the right is about 42 mm.

In Fig. 8 details of the track regions are shown. The clusterization structure is well visible. Because of the electron diffusion in the gas, track images are about 1 mm large.

In order to get an idea about the amount of detected light a simple analysis was performed. Figure 9 shows the distribution of the light detected by the pixels in the track region and by pixels not illuminated by the track for the event on the right in Fig. 7. The superimposed gaussian fit demonstrates that the response of not illuminated pixels is 99 ± 2 counts in good agreement with the result obtained in the dark condition (Sect. 3.1). The illuminated pixels, when properly accounted for the dark noise subtraction, are hence detecting up to 30 photons each.

The total amount of light integrated by the pixels in the track region was thus evaluated by studing the recorded images. It was measured that the linear light collection density is of about 600 ± 60 photons per track millimeter. According to the simulation results (Sect. 1.2) 7.7 primary

[4]17mm FL, f/0.95, Fast C-Mount. For more details visit https://www.schneideroptics.com

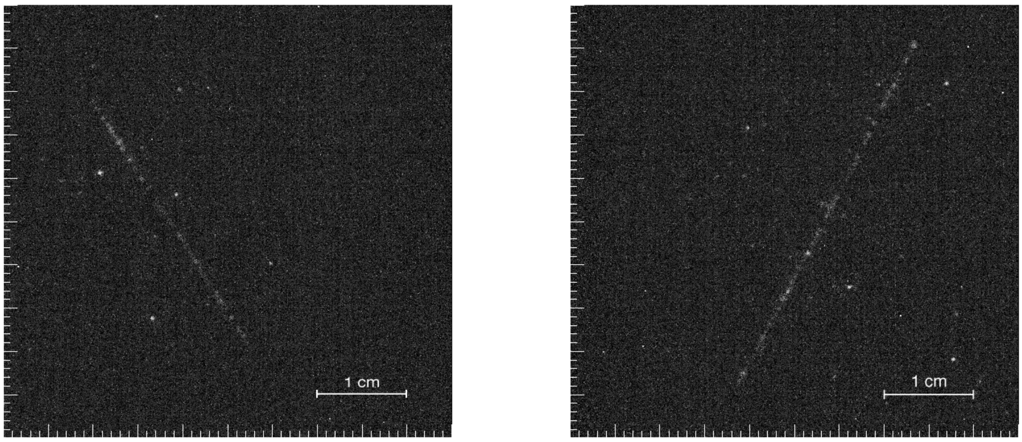

Figure 7. Examples of cosmic track images acquired by the CMOS based camera.

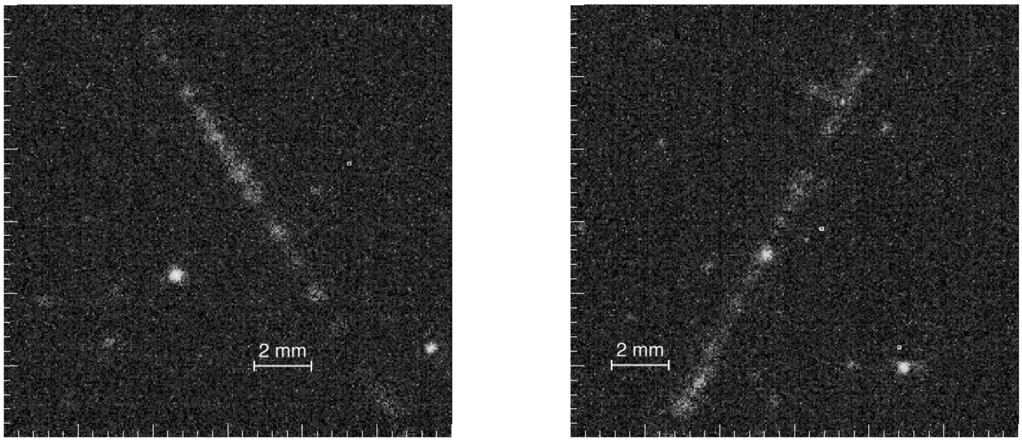

Figure 8. Zoom on the track images acquired by the CMOS based camera.

electrons are produced per millimeter by a cosmic ray. Therefore about 80 photons are detected per primary electron.

The maps of the pixels with a response three sigmas larger than the pedestal (i.e. higher than 105 counts), are shown Fig. 10. The tracks are well visible. From the analysis of all the recorded muon tracks, an amount of 40$\pm$5 pixels satisfying the above requirement per track millimeter was measured.

3.3 Electron measurements

During the data taking, several images of short, intense and curved tracks were acquired. These tracks (as the ones shown in Fig. 11) are very likely due to ionizing electrons produced by natural

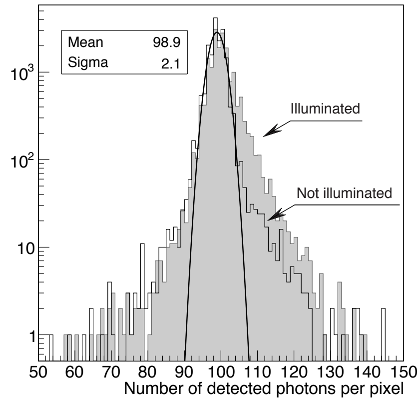

Figure 9. Distributions of the pixel response inside and outside the region illuminated by the track.

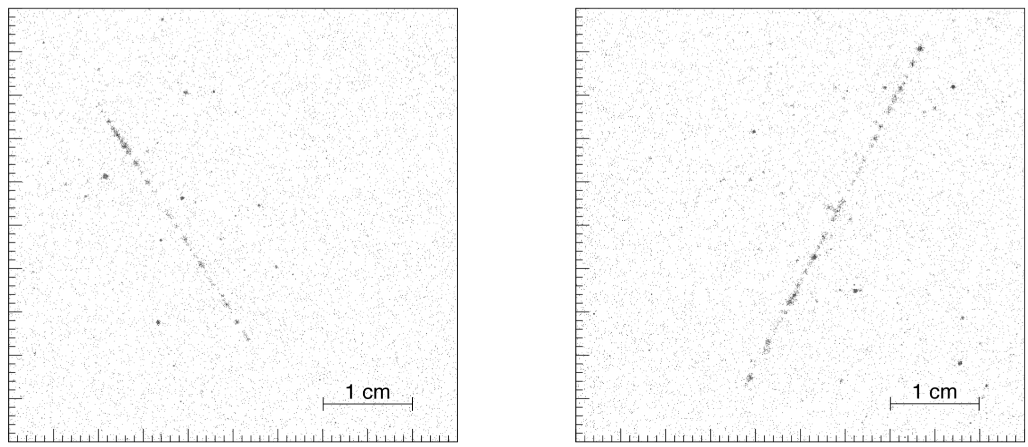

Figure 10. Maps of the pixels with a response larger than 105 counts (i.e. three sigmas larger than the pedestals).

radioactivity and traveling within the drift gap. Tracks shown in Fig. 11 are long approximatively 2.7 cm (left) and and 1.6 cm (right). As described in sect. 3.2 the maps of pixels collecting an amount of light larger than three sigmas above the pedestal were constructed. The results are shown in Fig. 12

As it is visible from the their intensities, the ionization density of these tracks is quite larger than the ones produced by cosmic ray muons. An amount of about 300 pixels three sigmas above the pedestal per track millimeter was measured.

4. Conclusion

The light yield of a triple-GEM stack in a He/CF_4 gas mixture was studied. After a suitable optimization of the electric fields, a total amount of about 2500 photo-electrons was detected by means

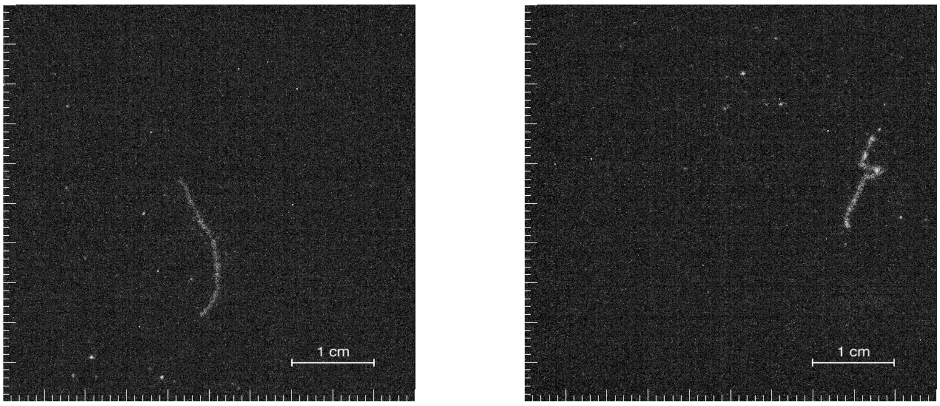

Figure 11. Examples of electron tracks.

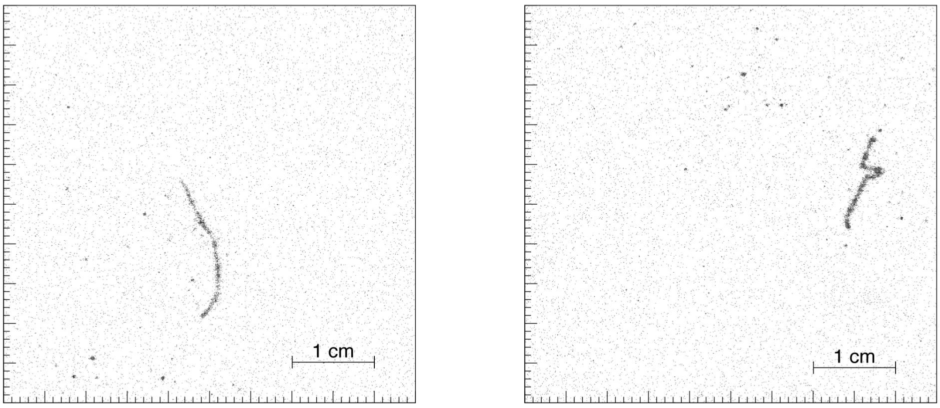

Figure 12. Maps of the pixels with a response larger than 105 counts (i.e. three sigmas larger than the pedestals).

of a PMT for a cosmic ray muon crossing a 3 mm wide gas gap. Images of emitted light were recorded by a CMOS sensor. Thanks to its very high sensitivity it has been possible to detect light on a large quantity of pixels. Muon tracks, several centimeter longs, where recorded. For these minimum ionizing particles average, in each track millimeter, more than 600 photons are detected making more than 30 pixels give a response three sigmas above the pedestal. Low energy electrons, due to natural radioactivity, were also detected. In these images, the amount of illuminated pixels is about ten times larger.

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